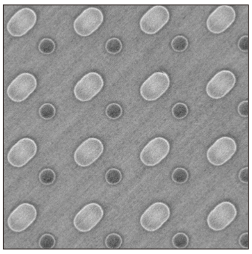

1.3-μm-Wavelength Photonic-Crystal Surface-Emitting Lasers

Yuhki ITOH*, Takeshi AOKI, Kosuke FUJII, Rei TANAKA, Makoto OGASAWARA, and Hiroyuki YOSHINAGA

To address the rapid increase in data traffic, data centers have increased the number of channels. However, current systems use one semiconductor laser per channel, resulting in higher power consumption and costs due to the increased number of components. To overcome these challenges, a new approach has been proposed, where light from a single laser with high output power is branched to create multiple channels. However, existing telecommunication lasers have reached the limit in achieving high output power with single-mode lasing. Therefore, we have conducted research on 1.3-*μ*m-wavelength InP-based photonic-crystal surface-emitting lasers (PCSELs) as a next-generation semiconductor laser that can achieve both single-mode lasing and high output power. We have demonstrated single-mode operation with a high output power of over 200 mW under continuous-wave conditions at room temperature by using dry-etching and regrowth techniques. In addition, we have achieved a high output power of 4.6 W in short-pulsed operation. These results suggest that PCSELs can be used not only for communications but also for sensing applications.

Keywords: photonic crystal, surface-emitting laser, photonic crystal laser, InP, regrowth

1. Introduction

Network traffic volume continues to increase due to the widespread use of smartphones, the growing popularity of social media networks and video streaming services, and shifts in work styles such as remote work. To support these services, data centers have increased the number of channels in order to handle the increasing network traffic volume. However, this has led to rising costs due to higher power consumption and an increasing number of components due to the use of one semiconductor laser per channel. To address these issues, a new approach has been proposed. This approach involves branching the light from a single laser with high output power to create multiple channels. However, current telecommunication lasers have reached their limit in terms of achieving high output power with single-mode lasing. Therefore, the development of a next-generation semiconductor laser is necessary to overcome the limitations of existing technology.

Against this backdrop, we are collaborating with Kyoto University on research and development of photonic-crystal surface-emitting lasers (PCSELs) as next-generation semiconductor lasers to achieve single-mode and high-power operation. Gallium arsenide (GaAs) -based PCSELs at a wavelength of ~940 nm have already been demonstrated as a single-mode lasing with a high output power of ~10 W.[1],[2] We have extended this technology to InP-based PCSELs in the wavelength range of 1.3 μm to 1.55 μm, which are suitable for telecommunication and eye-safety applications. In this paper, we first describe the operating principle and features of the PCSELs. Then, the fabrication process and the lasing characteristics of InP-based PCSELs are explained. By utilizing an optimized dry-etching and regrowth techniques, we have successfully demonstrated several key achievements, such as single-mode lasing under continuous-wave (CW) conditions at room temperature,[3] single-mode lasing with a high output power of over 200 mW by introducing a double-lattice photonic crystal,[4],[5] and watt-class high-power operation under short-pulsed conditions.[6]

2. Lasing Principle of Photonic-Crystal Surface-Emitting Lasers

Figure 1 (a) shows the device structure of the InP-based PCSELs. In PCSELs, a two-dimensional (2D) photonic crystal (PC)*1 is introduced near an active layer, which enables the formation of stable 2D standing waves (or cavity modes) at its singularity point (Γ point in Fig. 1 (b)). The 2D cavity mode is constructed through a direct 180° optical coupling and 90° indirect optical coupling as illustrated in Fig. 1 (c), and the cavity mode is coupled out to a vertical direction. Consequently, PCSELs exhibit stable single-mode lasing, even in a broad-area cavity with a diameter of several millimeters. Figure 2 compares the features of the PCSELs with conventional lasers, such as distributed feedback (DFB) edge-emitting lasers, and vertical-cavity surface-emitting lasers (VCSELs). To obtain high power with DFB lasers, it is necessary to extend the length of the resonator and widen the stripe width. However, this approach is limited by the design of the grating with a low optical coupling coefficient, and also suffers from the issue of multi-mode lasing. Similarly, VCSELs can increase output power by enlarging the aperture diameter, but also face the problem of multi-mode lasing. Thus, conventional lasers have a tradeoff between single-mode lasing and high output power. This tradeoff is due to the limitations of cavity size, as the direction of optical resonance is restricted to one direction and coincides with the direction of optical emission. In PCSELs, the cavity size can be increased thanks to a 2D optical resonance, and the optical light radiate in a vertical direction; therefore, the design flexibility improves because the direction of optical resonance differs from the direction of optical emission. By utilizing a properly designed PC, it is possible to effectively eliminate higher-order modes, leading to a single-mode lasing with high output power from large-area devices. Additionally, PCSELs are capable of emitting highly collimated beams with a narrow divergence angle of 1° or less, thanks to the large-area coherent resonance. Narrow beams are expected to reduce the number of lenses and other optical components in telecommunication systems, potentially lowering the cost.

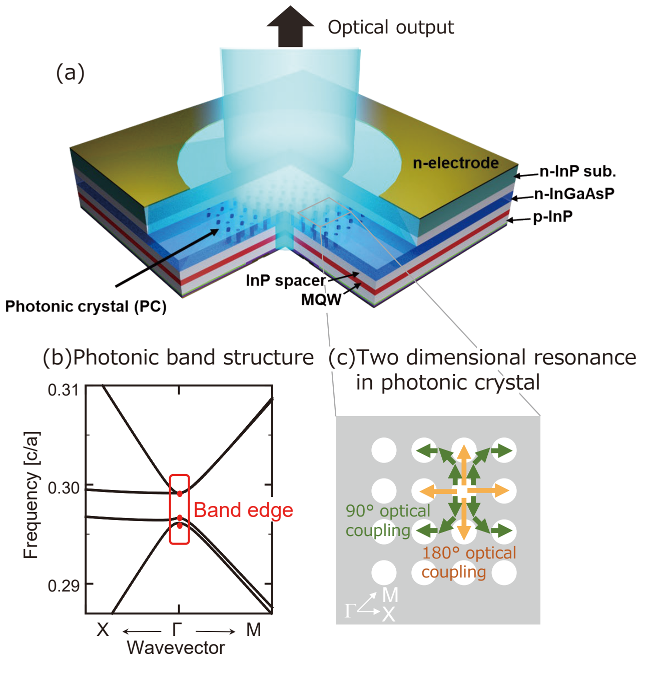

Fig. 1. (a) Device structure of InP-based PCSEL, (b) photonic band structure, (c) in-plane optical coupling within PC layer

3. Device Fabrication Process and Air-Hole Formation

3-1 Device fabrication process

The device fabrication process of the InP-based PCSEL is the following. First, an n-InGaAsP layer is grown on an n-InP substrate through metalorganic vapor-phase epitaxy (MOVPE). Then, a 2D double-lattice PC structure is formed in the n-InGaAsP PC layer by using electron-beam lithography and dry etching processes. The lattice constant (a) of each lattice is set to ~400 nm in order to operate at a wavelength of 1.3 µm. After the PC forma-

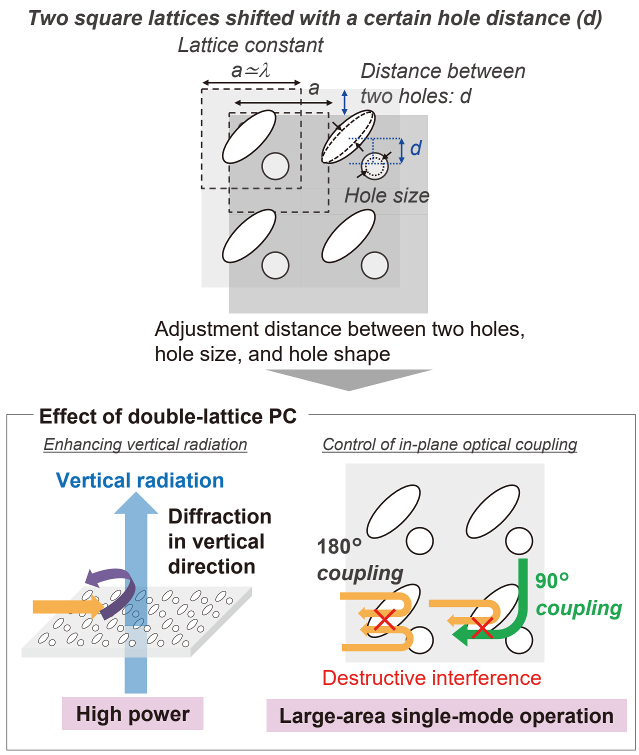

Fig. 3. Concept of double-lattice photonic crystal

	DFB laser	VCSEL	PCSEL
Light emission (resonance) direction	Optical resonance Light emission	Light emission Optical resonance	Broad-area coherent optical resonance
Method of increase in output power	· Increasing cavity length ⇒Limitations of grating design · Widening mesa width ⇒Multi-mode lasing	· Increasing aperture diameter ⇒Multi-mode lasing	· Increasing aperture diameter ⇒Single-mode lasing thank to PC
Spectra at high power	Multi-mode	Multi-mode	Single-mode
Beam divergence angle	Broad beam (20~30°)	Broad beam (5~20°)	Narrow beam (~1°)

Fig. 2. Features of PCSEL

tion, an InP overgrown layer (spacer layer), an InGaAsP multiple-quantum-well (MQW) active layer, a p-InP over-cladding layer, and a p^+-GaInAs contact layer are grown atop a 2D PC by MOVPE regrowth. The diameter of the p-electrode, which determines the current injection area, is set to 200 µm. In order to achieve optical emission from the substrate side, an n-electrode with a circular window is formed. A double-lattice PC structure, consisting of pairs of elliptical and circular air holes in each unit cell (as shown in Fig. 3), is used to increase the efficiency of surface emission by enhancing the asymmetry of PC. In this PC structure, two square lattice PCs are shifted with a certain distance (d) of the holes. In GaAs-based PCSELs, high output power has been demonstrated by introducing a double-lattice PC, which enhances vertical emission through its asymmetric nature of the double-lattice PC.(2) We have adopted this double-lattice PC for the first time in the InP-based PCSELs and optimized the distance and shape of holes to achieve high output power with single-mode lasing.

3-2 Formation of high-aspect-ratio deep air holes

Figure 4 shows the fabrication flow of the formation of air holes. An atomic force microscope (AFM) image after InP spacer growth, and a cross-sectional scanning electron microscope (SEM) image after the regrowth of MQWs are also shown in Fig. 4. The feature of our PCSEL is that the high-aspect-ratio deep air holes are formed under the active layer via a thin InP spacer. This structure avoids dry-etching damage to the active layer, as illustrated in Fig. 4. By optimizing dry-etching conditions, we have successfully achieved the formation of deep air holes with a depth of over 400 nm with a small diameter of 100 nm, which is required for the formation of double-lattice PC.(7) Moreover, we have also optimized regrowth conditions for the formation of the air holes, resulting in the formation of atomically flat surfaces even on the PC with a thin InP spacer thickness of below 100 nm by enhancing lateral growth.(3) By adopting these optimized dry-etching and regrowth conditions, deep air holes with a high aspect ratio of over 5 have been formed. The depth of elliptical holes is 600 nm, and that of circular holes is 450 nm. As a result of this investigation, it is possible to form a sufficient thickness of a PC layer near the active layer. This enables high optical confinement for both the PC layer and the active layer, making it possible to design PCSELs with high optical coupling coefficients.

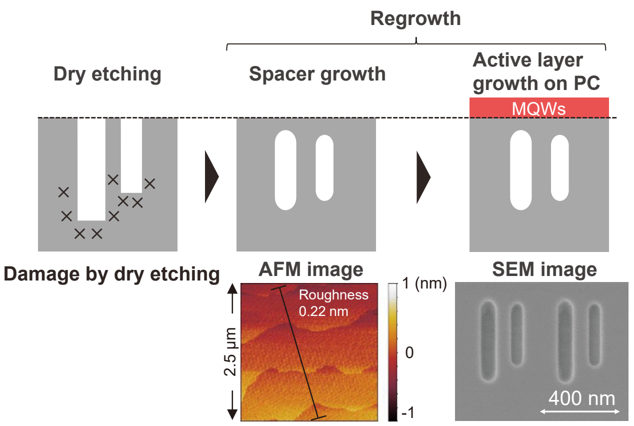

Fig. 4. Fabrication flow of formation of air holes. AFM image after regrowth of InP spacer and cross-sectional SEM image after regrowth of MQWs are also shown

4. Lasing Characteristics

Figure 5 shows the light output - current (L-I) characteristics of the double-lattice InP-based PCSEL under pulsed conditions with a pulse width of 1 µs and a duty cycle of 0.1% at 25°C. The L-I characteristic of a single-lattice PCSEL with circular air holes in the same device configuration is also shown as a reference. The optical power of the double-lattice PCSEL is much higher than that of the single-lattice PCSEL, and the slope efficiency of the double-lattice PCSEL is 25 times higher than that of the single-lattice PCSEL. These results indicate that the introduction of the double-lattice PC is effective to enhance the slope efficiency as designed owing to the asymmetry of the PC structure.

Figure 6 (a) presents the L-I characteristics of the double-lattice PCSEL under CW conditions at temperatures from 25°C to 80°C. The lasing occurs at a threshold current (I_{th}) of 230 mA (threshold current density (J_{th}): 730 A/cm^2) at 25°C, and the output power is 240 mW. The maximum slope efficiency at 25°C is 0.21 W/A, and the maximum power conversion efficiency is 11%. In PCSELs, the

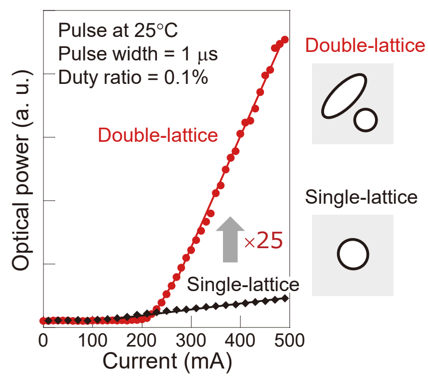

Fig. 5. L-I characteristics under pulsed operation at room temperature (Pulse width: 1 µs; Duty ratio: 0.1%)

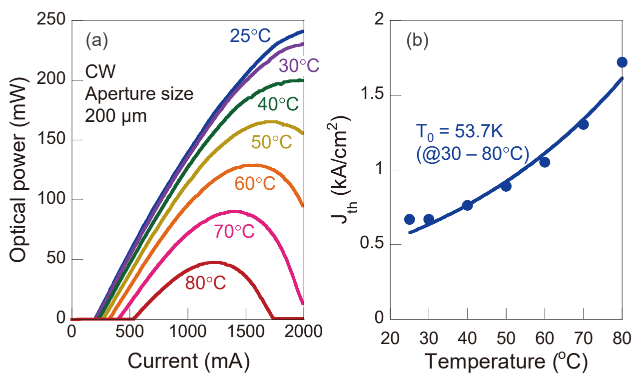

Fig. 6. (a) L-I characteristics of double-lattice PCSEL under CW conditions and (b) temperature dependence of threshold current density

emitted light is diffracted upwards and downwards in principle. By introducing a reflective mirror to reflect the light towards the emission side, the optical power and slope efficiency can be increased. Figure 6 (b) plots the temperature dependence of the threshold current density. The characteristic temperature*2 (T_0) is estimated from the temperature dependence of the threshold current density with a temperature range of 30°C to 80°C, and its value is 53.7 K. This value is almost the same as those of conventional InP-based DFB lasers, indicating that the temperature characteristics of the PCSEL are comparable to those of DFB lasers.

Figure 7 (a) shows lasing spectra under CW conditions at 25°C, 50°C, and 80°C. The injection currents are set to be close to the maximum optical power. Single-mode lasing is obtained at all temperatures, even at a high output power. The side-mode suppression ratio (SMSR) exceeds 48 dB. We have also confirmed that single-mode lasing occurs at the low-current injection near the threshold current. These results suggest that the PCSEL exhibit mode-hop-free operation. Figure 7 (b) plots the temperature dependence of lasing wavelength shift. The wavelength is shifted to longer wavelengths, with a wavelength shift of 0.103 nm/K, which is almost comparable to InP-based DFB lasers.

Figure 8 shows far-field patterns (FFPs) emitted from PCSEL at an injection current of 1000 mA under CW conditions at 25°C and 80°C. A circular beam with a narrow divergence angle of below 1.5° is observed in a temperature range of 25°C to 80°C. This result indicates that single-mode lasing with narrow circular beams, which is the unique feature of PCSELs, is maintained even at a high temperature of 80°C.

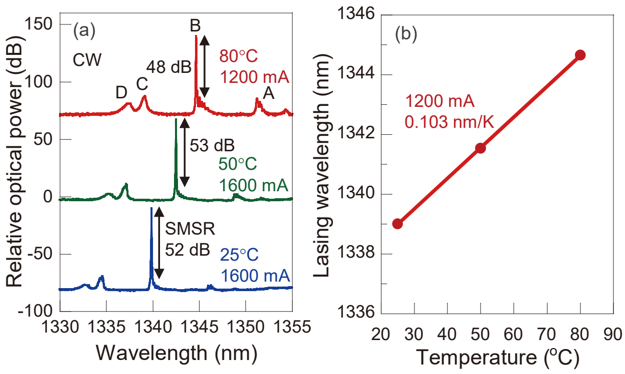

Fig. 7. (a) Lasing spectra of double-lattice PCSEL under CW conditions and (b) temperature dependence of lasing wavelength

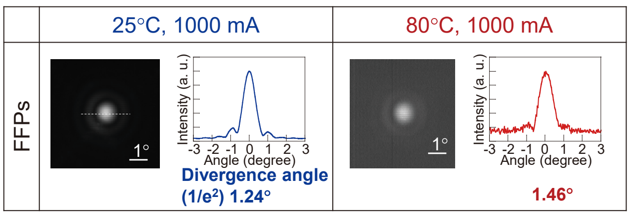

Fig. 8. Far-field patterns at an injection current of 1000 mA under CW conditions at 25°C and 80°C

The narrow circular beam is also expected to contribute to the improvement of spatial resolution and ranging distance in sensing applications, especially as light sources for light detection and ranging (LiDAR). In the case of time of flight (ToF)-system LiDAR applications, lasers are operated under short-pulsed conditions with a pulse width on the order of nanoseconds. Therefore, as an initial evaluation on InP-based PCSELs for sensing applications, we have measured the *L-I* characteristics under short-pulsed conditions. Figure 9 shows the *L-I* characteristics of the double-lattice InP-based PCSEL at room temperature under short-pulsed conditions with pulse widths of 2 µs and 20 ns and a pulse cycle of 1 ms. For a pulse width of 2 µs, the optical power is saturated at an injection current of 5 A, and the optical power is 700 mW. On the other hand, for a pulse width of 20 ns, a significantly high peak power of 4.6 W is achieved at the upper limit of the injection current of 35 A. This peak power represents the highest power ever obtained with an InP-based PCSEL. It is worth mentioning that even higher peak power could be achieved by using shorter pulse conditions, increasing the device size, or optimizing the PC design for pulsed operation.

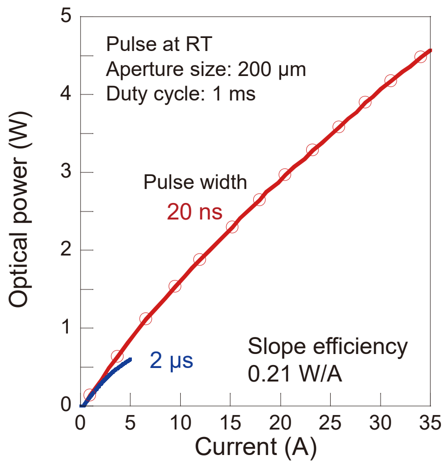

Fig. 9. *L-I* characteristics under short-pulsed conditions

Figure 10 shows the measured photonic band structure of the InP-based double-lattice PCSEL in the vicinity of the Γ point at an injection current below threshold under the pulsed condition with a pulse width of 1 µs and a duty cycle of 0.1% at room temperature (RT). The band structure is obtained from spontaneous spectra for each angular point, which corresponds to the in-plane wavenumber.(8) The formation of four band-edge modes (A, B, C, and D in increasing order of frequency) that reflect square-lattice PC is clearly observed. The lasing mode is identified at band-edge mode B from a comparison of the spectra below and above the threshold. To evaluate the strength of optical coupling within the PC structure, we have estimated the in-plane optical coupling coefficients for 180° (κ_{1D}) and 90° (κ_{2D}^{+} and κ_{2D}^{-}) diffractions from each band-edge frequencies.(2) The estimated κ_{1D}, and κ_{2D}^{+}, and κ_{2D}^{-} are 522 cm^{-1}, 193 cm^{-1}, and 131 cm^{-1}. We have validated these values by using a rigorous coupled-wave analysis (RCWA),[9] which yielded coupling coefficients (κ_{1D}, κ_{2D}^{+}, κ_{2D}^{-}) of 490 cm^{-1}, 175 cm^{-1}, and 141 cm^{-1}, respectively. The simulated values are consistent with the measurements, indicating that the PC has been formed as designed. We consider that the realization of relatively high κ_{2D} of 100 cm^{-1} owing to the high-aspect-ratio deep air holes led to single-mode lasing with a high SMSR in a wide operating temperature range.

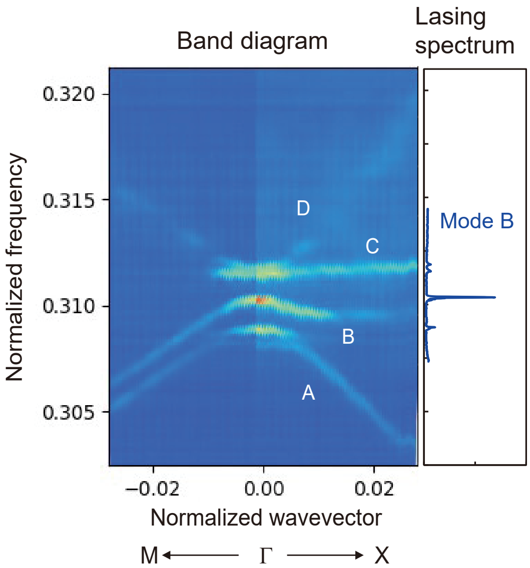

Fig. 10. Photonic band structure of fabricated PCSEL

5. Conclusion

We have demonstrated high-power single-mode lasing from 1.3-µm-wavelength InP-based double-lattice PCSELs. The optical power of 240 mW has been achieved with single-mode and a narrow circular beam under CW conditions at room temperature. The high peak power of 4.6 W has been also exhibited under short-pulsed operation. These results prove that InP-based PCSELs are promising as a light source for optical communications and sensing applications.

6. Acknowledgments

This work was carried out as a joint research project with Professor Noda at the Center of Excellence (COE) for Photonic-Crystal Surface-Emitting Laser, Kyoto University.

Technical Terms

*1 Photonic crystal: A periodic structure designed to control the propagation state of light; by fabricating it at a period resembling a wavelength of light inside the material, it becomes possible to either confine or guide light of a particular wavelength.

*2 Characteristic temperature: An indicator of the basic characteristics of a laser; a higher characteristic temperature indicates that lasing is available at higher temperatures.

References

(1) S. Noda, K. Kitamura, T. Okino, D. Yasuda and Y. Tanaka., "Photonic-crystal surface-emitting lasers: Review and introduction of modulated-photonic crystals," IEEE J. Sel. Top. Quantum Electron. 23(6) (2017)

(2) M. Yoshida, M. De Zoysa, K. Ishizaki, Y. Tanaka, M. Kawasaki, R. Hatsuda, B. Song, J. Gelleta and S. Noda., "Double-lattice photonic-crystal resonators enabling high-brightness semiconductor lasers with symmetric narrow-divergence beams," Nat. Mater. 18(2), 121–128 (2019)

(3) Y. Itoh, N. Kono, N. Fujiwara, H. Yagi, T. Katsuyama, T. Kitamura, K. Fujii, M. Ekawa, H. Shoji, T. Inoue, M. De Zoysa, K. Ishizaki and S. Noda., "Continous-wave lasing operation of 1.3-µm wavelength InP-based photonic crystal surface-emitting lasers using MOVPE regrowth," Opt. Express 28(24), 35483 (2020)

(4) Y. Itoh, N. Kono, K. Fujii, H. Yoshinaga, N. Fujiwara, M. Ogasawara, R. Tanaka, H. Yagi, M. Yanagisawa, M. Yoshida, T. Inoue, M. De Zoysa, K. Ishizaki and S. Noda., "High-Power Single-Mode Operation of 1.3 µm Wavelength Double-Lattice Photonic-Crystal Surface-Emitting Lasers using InP-based Regrowth Process," Conf. Dig. - IEEE Int. Semicond. Laser Conf. 2022-Octob, Institute of Electrical and Electronics Engineers Inc. (2022)

(5) Y. Itoh, N. Kono, D. Inoue, N. Fujiwara, M. Ogasawara, K. Fujii, H. Yoshinaga, H. Yagi, M. Yanagisawa, M. Yoshida, T. Inoue, M. De Zoysa, K. Ishizaki and S. Noda., "High-power CW oscillation of 1.3-µm wavelength InP-based photonic-crystal surface-emitting lasers," Opt. Express 30(16), 29539 (2022)

(6) Y. Itoh, N. Kouno, K. Fujii, H. Yoshinaga, N. Fujiwara, M. Ogasawara, R. Tanaka, H. Yagi, M. Yanagisawa, M. Yoshida, T. Inoue, M. De Zoysa, K. Ishizaki and S. Noda., "High-power with single-lobe beam of 1.3-µm InP-based double-lattice photonic-crystal surface-emitting lasers," Proc. SPIE Photonics West 12440, 124400E (2023)

(7) Y. Itoh, N. Kono, N. Fujiwara, H. Yagi, T. Katsuyama, D. Inoue, K. Fujii, M. Ekawa, H. Shoji, T. Inoue, M. De Zoysa, K. Ishizaki and S. Noda., "Low-Threshold Single-Mode Lasing from InP-based Double-Lattice Photonic Crystal Surface Emitting Lasers with High-Aspect-Ratio Air Holes," Conf. Dig. - IEEE Int. Semicond. Laser Conf. (2021)

(8) K. Sakai, E. Miyai, T. Sakaguchi, D. Ohnishi, T. Okano and S. Noda., "Lasing band-edge identification for a surface-emitting photonic crystal laser," IEEE J. Sel. Areas Commun. 23(7), 1335–1340 (2005)

(9) V. Liu and S. Fan., "S4 : A free electromagnetic solver for layered periodic structures," Comput. Phys. Commun. 183(10), 2233–2244 (2012)

Contributors
The lead author is indicated by an asterisk (*).

Y. ITOH*
• Ph. D.
Transmission Devices Laboratory

T. AOKI
• Ph. D.
Assistant Manager, Transmission Devices Laboratory

K. FUJII
• Assistant Manager, Transmission Devices Laboratory

R. TANAKA
• Assistant Manager, Transmission Devices Laboratory

M. OGASAWARA
• Transmission Devices Laboratory

H. YOSHINAGA
• Group Manager, Transmission Devices Laboratory